

Performance of Different Models for Estimating the Global Solar Radiation in Brazil

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Abstract— Global solar irradiance (Q_g) is an important variable of the physical environment that has been constantly used in agrometeorological models, either for climatic characterization or to give support to radiometric studies developed for irrigation planning and crop weather modeling approaches. The current study aimed to compare measured daily values of Q_g with estimates of this variable by means of four different methods. For that throughout the period comprised between March 28th of 2008 and August 8th of 2011 at Ponta Grossa, PR, Brazil, a simple linear regression study confronting radiometric data measured by a pyranometer and estimates of Q_g was proposed herein. Global transmittance was conditioned by atmospheric cloudiness. The models based on mean global transmittance in daily basis performed more satisfactorily and generated values of Q_g with accuracy and exactness at the site in study, as confirmed by the statistical parameters employed to validate the usage of models proposed by Angström-Prescott. However, the performance of the methodologies based on the determination of mean global transmittance under extreme atmospheric conditions, showed the highest Willmott coefficients, which was to be close to 1, reflecting then precision and reliability for the calculated values of Q_g , when compared to observed values monitored at an automatic weather station.

Keywords— Solar radiation, global transmittance, modeling, sustainable agriculture.

I. INTRODUCTION

Solar irradiance is responsible for triggering great part of the chemical, physical and biological processes in the soil-plant-atmosphere system. However, not all solar irradiance can effectively reach terrestrial surface, for by passing through optical mass and interacting with the atmospheric components it suffers action of reflection, diffusion and absorption processes. From such, approximately 51% of the extraterrestrial solar irradiance is available to be utilized in processes of the biological and physical environment (Ometto, 1981), depicting the fraction of radiation that effectively reaches soil surface or global solar radiation (Q_g).

Q_g is an important variable of the physical environment that is constantly employed in studies of water requirement of irrigated crops, modeling of growth and crop yield, climate changes, optimization of environmental comfort, among other applications. The great problem dealing with collection of Q_g data is the high cost of the pyranometer, a radiometric equipment responsible for recording global solar irradiance at a given site (Souza et al., 2011). Moreover, the Q_g quantification requires the usage of recorders or data acquisition systems, as well as skilled and specialized people making the cost of such information high at operational level.

The lack of Q_g observations has been a persistent problem in studies of biophysical processes in agroecosystems. The number of weather stations recording the daily irradiance is small compared to the number of weather stations that monitor temperature and rainfall. In the United States of America the ratio of weather stations that measure solar radiation components and those that measure air temperature is greater than 1:100; in global terms such a ratio is of 1:500 (Thorton and Running, 1999). In the northeast of China, region of the country of a great agricultural importance, there are 109 weather stations, being that among those only 13 perform routine radiometric measurements (Wu et al., 2012). In the state of Paraná, Brazil, there are 37 automatic weather stations and 22 conventional weather stations responsible for the records of solar irradiance components. However, the electronic sensors are not always calibrated, showing record failures for a long period and lack of accurate radiometric information in studies related to micrometeorology and optimization of irrigation in agriculture.

Ratio between global solar irradiance and solar irradiance at the top of the atmosphere represents global solar transmittance, which in conjunction with insolation ratio might be employed in the Angström-Prescott equation to estimate the a and b empirical coefficients (which reflect the factors that affect absorption and diffusion of solar radiation) and that are considered as an input variable in estimation models of global irradiance for sites that do not count on equipment and specialized

labor throughout the collection of such a variable (Paulescu et al., 2008).

The Angström-Prescott equation proposed to estimate global irradiance from insolation ratio was idealized by Angström in 1924 and modified by Prescott sixteen years later with the purpose of circumventing the difficulty of obtaining the Angot value (Penman, 1948). Such equation, besides referring to a time interval higher than 70 years has demonstrated satisfactory performances for small periods all over the world and has been largely used in studies of solar radiometry (Li et al., 2011; Kolebaje and Mustapha, 2012; Wu et al., 2012; Sabziparvar et al., 2013), although some limitations are to be taken into account especially due to cloud thickness.

Recently Li et al. (2011), making use of the classical model of Angström-Prescott for estimating global solar irradiance in Tibet, China, from a series of 15 years of radiometric data at four different weather stations, obtained estimates of the variable in question with errors lower than 10% in all studied sites. Wu et al. (2012), using the same model for assessing Q_g throughout the crop growing season at the northeast of China, concluded that such a calculation procedure is not only effective and reliable but also an economic means to obtain radiometric data where the collection of such an environmental variable is scanty.

Kolebaje and Mustapha (2012) obtained a high accuracy for the Q_g estimation model proposed by Angström-Prescott at four different climatic regions of Nigeria. The reliability and performance of the Angström-Prescott model were also evidenced by Namrata et al. (2013), by comparing such a model to other six empirical models for estimating global irradiance at the region of Jharkhand, India. Sabziparvar et al. (2013) made use of the model proposed by Angström-Prescott to estimate global irradiance at 15 sites of Iran with the purpose of using it for the calculation of reference evapotranspiration and verified that such a classical estimation model was precise to assess Q_g .

Aiming at examining the performance of different models for the calculation of monthly and daily solar irradiance at a horizontal surface in Kuala Terengganu, Malaysia, Muzathik et al. (2011) observed that by means of the mean percent error, mean squared error of the Fisher correlation test and t-test the estimation model proposed by Angström-Prescott was ascribed by low dispersion measures, revealing a high precision and reliability under the studied climatic conditions.

Scientists from all over the world have been incorporating modifications into the Angström-Prescott classical model by means of the insertion of physical variables or alterations in the mathematical expression of Q_g calculation in order to improve accuracy and exactness of the estimates so that reliability and feasibility

might be assured under specific atmospheric conditions at several sites of the globe (Newland 1989; Ampratwum and Dorvlo, 1999; Almorox and Hontoria, 2004; Şen 2007; Bakirci, 2009; Chineke and Okoro, 2010).

In order to meet the needs of knowing solar energy availability at the region of Campos Gerais of Parana, Brazil, we come up with mathematical models developed to estimate global solar irradiance, which differ among themselves in terms of complexity and number of input variables of the model. It is important to consider that such models are in general applicable to environmental conditions where they were originally developed, showing therefore problems of transferability when not properly gauged and calibrated (Borges et al., 2010).

Faced with that, the current work aimed to determine global transmittance, evaluate and compare the performance of four different models for estimating Q_g under the climatic conditions of Ponta Grossa, State of Parana, Brazil, in order to maximize crop yield at production fields with environmental protection.

II. MATERIAL AND METHODS

The field trial was carried out at the Experiment Station of the State University of Ponta Grossa, Ponta Grossa, PR, Brazil (altitude of 880m, latitude of 25°5'S and longitude of 50°3'W). The local climate was classified according to Köppen's classification as of the type Cfb – humid subtropical climate.

Global solar irradiance daily data was measured by a silica photodiode pyranometer, LI-COR, model LI-200X, with a spectral response within the interval of 0.4 and 1.2 μm , with a typical absolute error of $\pm 3\%$ (Federer and Tanner, 1965) from a automatic weather station throughout the period comprised between March 28th of 2008 and August 24th of 2011. The pyranometer was coupled to a Campbell Scientific Inc., model CR-1000, data acquisition system programmed for taking readings with a 60 s frequency and storing averages at each 30 minutes. Initially instantaneous values of Q_g were integrated (W m^{-2}) over the course of a day in such a way as to express them in $\text{MJ m}^{-2} \text{day}^{-1}$.

In order to estimate the extraterrestrial solar irradiance in $\text{MJ m}^{-2} \text{day}^{-1}$ the following expression was used:

$$Q_0 = 37.6 (d/D)^2 [(\pi/180^\circ) \text{hn} \sin \Phi \sin \delta + \cos \Phi \cos \delta \sin \text{hn}] \quad (1)$$

$$(d/D)^2 = 1 + 0.033 \cos (\text{DOY } 360/365) \quad (2)$$

where:

Φ = local latitude (degrees); δ = solar declination (degrees); hn = hourly angle at the sunrise (degrees); d/D = Earth-Sun relative distance, being d the average distance and D the actual distance; DOY = day of the year.

The photoperiod duration was determined by means of Pereira and Villa Nova (2008) and effective astronomical insolation was measured by a Campbell Stokes heliograph daily integrated from heliograms during the period of analysis.

In order to calculate daily global transmittance daily values of global solar irradiance were divided by daily extraterrestrial solar irradiance. Afterwards the same calculation procedure was repeated so as to classify the radiometric data into cloudy and sunny days as a function of insolation ratio, which was lower than 0.3 for cloudy days and higher than 0.8 for sunny days.

To estimate Q_g four different models were employed in the current research.

1st Model – Q_g estimation as a function of the mean global transmittance (\overline{Tg}) for clear and completely overcast days (Pereira et al., 2002). Taking into consideration a series of radiometric data available at the studied site for clear days, \overline{Tg} was expressed by: $\overline{Tg} = a + b = 0.618$. For completely overcast days, $\overline{Tg} = a = 0.143$. Based on such empirical regression equation coefficients, global solar irradiance was obtained by:

$$Q_g = Q_o * [0.143 + 0.475 * \frac{n}{N}] \quad (3)$$

where,

$\frac{n}{N}$ is the insolation ratio given by the rate between effective astronomical insolation (n) and photoperiod duration (N).

2nd Model – Q_g estimation as a function of the daily mean global transmittance (\overline{Tg}) for clear days in compliance with the first model, and considering the latitudinal dependence of a proposed by Glover and McCulloch (1958). Thus, global solar irradiance was obtained by:

$$Q_g = Q_o * [0.262 + 0.356 * \frac{n}{N}] \quad (4)$$

3rd Model – Based on the maximum global transmittance obtained from only one radiometric measurement taken at solar noon ($Tg_{max_{(12)}}$) (Pereira et al., 2003):

$$Q_g = Q_o * [0.262 - b' * \frac{n}{N}] \quad (5)$$

where:

$$b' = Tg_{max_{(12)}} - 0.262 \quad (6)$$

4th Model – Based on the classical proposition of Glover and McCulloch (1958), being defined by:

$$Q_g = Q_o * [0.29 * \cos\phi + 0.52 * \frac{n}{N}] \quad (7)$$

The accuracy of the estimates of Q_g was expressed by the coefficient of determination (R^2) (Legates and McCabe, 1999). Its exactness might be observed by the

dispersion of the data around the fitted line of the estimates in a 1:1 graph, which was quantified by means of the agreement index (d) proposed by Willmott et al. (1985), once the values of coefficient of correlation and determination analyzed separately can lead to interpretations not always suitable for the performance of the studied model.

In this paper, a new index c proposed by Camargo and Sentelhas (1987) was also adopted to indicate the performance of the Q_g model, putting together the accuracy R and exactness d indices, being defined by the multiplication between both statistical indices.

In order to evaluate the error of estimates two statistical parameters were calculated, such as the mean absolute percentage error (MAPE) and smoothed absolute percentage error (SAPE), as described by Goodwin and Lawton (1999). Moreover, to compare observed and predicted data of global solar irradiance the following errors were adopted: mean error (ME), mean absolute error (MAE) and root mean square error (RMSE) (Borges et al., 2010).

III. RESULTS AND DISCUSSION

Daily global solar transmittance (Tg) represents the proportion of global solar irradiance determined at the extreme limit of the atmosphere that effectively reaches soil surface. Since Tg comes from the interaction of Q_o with the terrestrial atmosphere it is certain that optical mass thickness varies in compliance with zenithal angle, which therefore brings about instantaneous fluctuations in Tg throughout the day, showing low values at sunrise and sunset and maximum values at noon, time of the day in which there will be the maximum incidence of solar energy at the Earth surface.

Another factor that it is to be of a great deal of concern on daily global solar transmittance of the atmosphere is cloudiness, once reflectivity of the clouds is greater than reflectivity of the atmosphere under cloudless conditions (Dantas et al., 2000). The influence of the clouds on Tg during the different seasons of the year was observed by Pereira et al. (2002), evidencing that Tg values were always lower under cloudy days (0.265) than under sunny days (0.770) at the municipality of Piracicaba, SP. In Ponta Grossa, PR, for all radiometric data series in study we verified that under cloudy days daily mean values of Tg were corresponding to 0.143, whereas under sunny days the highest daily mean values of Tg were of 0.618. Under cloudless conditions cloudiness is minimal or absent and insolation is maximum, being conducive to the highest possible Tg values.

In order to determine a clarity index under climatic conditions of Akure, Nigeria, Adaramola (2012) analyzed radiation ratio (Q_g/Q_o) and came up with the lowest

values of T_g for the period of time comprised between April and August (wet season), being capable of observing the opposite during the dry season at the studied site. Such an author along with Chaar and Lamont (2010) verified at three different regions of Abu Dhabi, United Arab Emirates, that during the months with a more pronounced cloudiness index (January through April) global transmittance was the lowest in conjunction with the highest T_g values obtained during those months under the lowest cloudiness condition.

Faced with a seasonal analysis on T_g calculated at Ponta Grossa, PR, it was possible to observe that T_g values under cloudy days were higher during spring/summer seasons, whereas under sunny days T_g was higher during fall/winter seasons (Table 1). The highest T_g values under sunny days throughout fall/winter time might be ascribed to the lowest cloudiness index for the region of Ponta Grossa at this time of the year, characterizing a dry season at the site. The lowest T_g values under sunny days during spring/summer seasons might be attributed to the highest amounts of rainfall at such a time of the year, which resulted in an increase in the atmospheric humidity in such a way as to accrue cloudiness conditions at the studied site.

Divergent outcomes of T_g were reported by Querino et al. (2011) in a radiometric study conducted in Alagoas State, where during the summer months atmospheric transmissivity was always higher than that observed during the period of time comprised between May and June (fall/winter seasons), with T_g values higher than 70%.

In a similar study, Pereira et al. (2002) calculated T_g for the same seasonal periods, however under climatic conditions of Piracicaba, SP. In a comparative study between both distinct local climatic conditions and taking into consideration the same period of time in analysis, we reached the conclusion that regardless of the season of the year Piracicaba, SP, showed a higher T_g in relation to Ponta Grossa, PR. The lowest T_g values for the studied site might be explained by the interference of cold fronts, probably the Atlantic Polar Mass or air masses coming from the ocean, as well as by the action of wet maritime winds influenced by the anticyclone from the South Atlantic, which in turn cause orographic rainfalls at Serra do Mar and also at a large extension of the State of Parana, Brazil (Beruski et al., 2009).

Table.1: Daily global solar transmittance (T_g) calculated for both cloudy and sunny days under the climatic conditions of Ponta Grossa, PR. Average throughout the studied period.

Global Transmittance	Ponta Grossa - Brazil	
	Spring/Summer	Fall/Winter

Cloudy days	0.152	0.142
Sunny days	0.610	0.622

Discrepancies in the variation of T_g also might be noticed as a function of local latitude. Thus, at sites of low latitudes the incidence of solar radiation is quite nearer the perpendicularity in relation to equator plan and, therefore, the saturation period of energy diminishes with the increase in latitude. Variations in global transmittance as a function of local latitude were also observed by Yousif et al. (2013), by comparing two distinct sites of Europe: Marsaxlokk in Malta and Valladolid, in Spain.

All Q_g estimation methods assessed in the current research showed values consistently close to those measured by the pyranometer (Figure 1).

By comparing the coefficients of determination (R^2) and the Pearson correlation (R) we noticed that all models studied demonstrated a high precision. The 4th model showed the highest value of R^2 , with 99.8% of the measured Q_g variations being explained by a simple linear regression equation, evidencing therefore a high precision for such a model. Either the coefficient of determination or Pearson correlation one bring only information about the precision of the mathematical models used, but nothing reveal about its exactness (Pereira et al., 2003; Pereira and Villa Nova, 2008). Therefore, by means of the calculation of the agreement index (d) proposed by Willmott et al. (1985) it was possible to notice that the 1st and 2nd models were related to values of d corresponding to 0.982 and 0.989, respectively, indicating that the estimated values of Q_g were extremely close to the observed ones. Although the agreement indices obtained for the 3rd and 4th estimation models had been low in comparative terms, such statistical parameters were also high for such models, assuming values close to 1, given the small dispersion of the data around the fitted 1:1 line (Figure 1).

The performance index (c) of the mathematical models, defined by the multiplication between R and d , was of 0.980 for the first model, 0.979 for the second, 0.839 for the third, and 0.942 for the forth model. Taking into account the interpretation criterion of performance of agrometeorological models proposed by Camargo and Sentelhas (1997), the performances obtained by the 1st, 2nd, and 4th estimation models were excellent ($c > 0.85$), whereas only the 3rd model was classified as that one with a very good performance (c ranging from 0.76 to 0.85).

Wu et al. (2012), making use of the Angström-Preseott model to estimate Q_g in the northeast of China, obtained values of coefficient of determination (R^2) between 0.77 and 0.89, depicting in average 83 % of the variations in observed values of Q_g and being explained by regression models proposed from radiometric data

collected from automatic weather stations installed at the studied site.

Kolebaje and Mustapha (2012), by analyzing the performance of different Q_g estimation models for four distinct sites in Nigeria, verified that the model proposed by Angström-Prescott showed a coefficient of correlation of 0.953 and 0.872 for the regions of Port Harcourt and Lokoja, respectively, and concluded that Q_g values

estimated by the model in study were those that the most depicted reality observed under the environmental conditions of this work. Similar results were obtained by Muzathik et al. (2011), who have found a coefficient of the Pearson correlation corresponding to 0.855 for the classical model employed to calculate Q_g , making it possible and feasible for assessment of the physical variable in question at Kuala Terengganu, Malaysia.

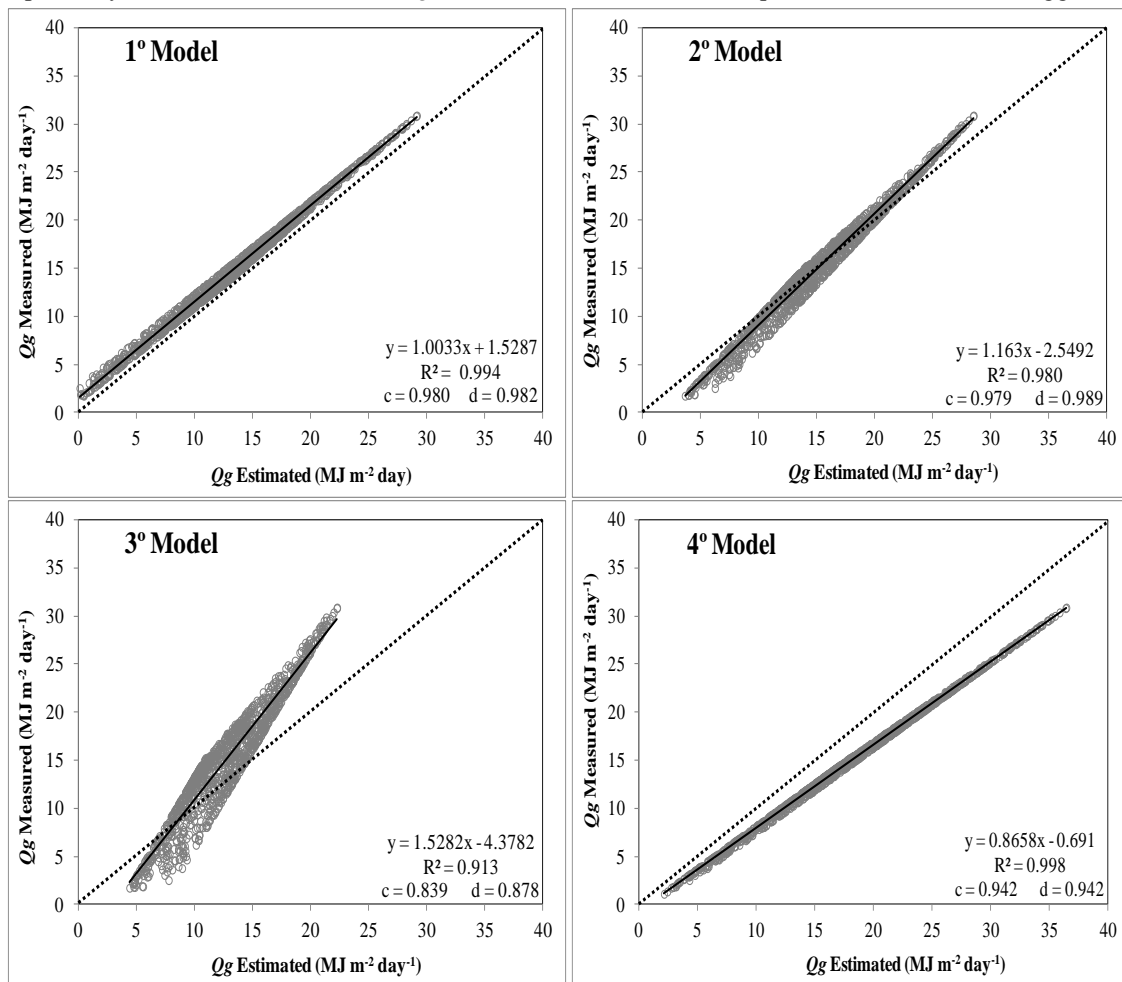


Fig.1: Relationship between daily global solar irradiance (Q_g) measured by a pyranometer and estimated by four different models under the climatic conditions of the municipality of Ponta Grossa, PR, Brazil.

Values obtained for the errors of estimates expressed by both mean absolute percentage error (MAPE) and smoothed absolute percentage error (SAPE) firm up the feasibility of utilization of four mathematical models proposed to estimate global solar irradiance under the climatic conditions of Ponta Grossa, PR, Brazil (Table

2). Nevertheless, the first and second models showed the lowest values of MAPE and SAPE, being lesser than 16%, whereas for the 3rd and 4th models such dispersion measures oscillated around 20 to 23%, reinforcing the recommendation of the two first models for radiometric and agrometeorological studies at the studied region.

Table.2: Mean absolute percentage error (MAPE), smoothed absolute percentage error (SAPE), mean error (ME), mean absolute error (MAE), and root mean square error (RMSE) calculated from the comparative analysis between daily global solar irradiance (Q_g) measured by a pyranometer and estimated by four different models under the climatic conditions of the municipality of Ponta Grossa, PR, Brazil.

Models	MAPE	SAPE	EM	MAE	RMSE
	%			$\text{MJ m}^{-2} \text{ dia}^{-1}$	
1 st	13.64	15.63	0.86	1.58	1.64
2 nd	10.61	9.25	1.06	0.99	1.21
3 rd	22.32	22.22	0.93	3.03	3.56
4 th	22.60	20.17	1.23	3.12	3.27

The confirmation that both first and second global solar irradiance estimation models were those that most reflected reality of radiometric data measured at an automatic weather station installed in Ponta Grossa, PR, Brazil, might be evidenced by the lowest values of mean absolute error (MAE) and root mean square error (RMSE) associated to such models (Table 2).

In general all models employed to estimate Q_g under the climatic conditions of Ponta Grossa, PR, demonstrated a trend to overestimating such environmental variable. The Q_g values of overestimation based on MAE varied from $0.99 \text{ MJ m}^{-2} \text{ day}^{-1}$ for the first model up to $3.12 \text{ MJ m}^{-2} \text{ day}^{-1}$ for the forth model. Corroborating MAE, calculated values of RMSE also revealed a low error in the estimates of Q_g from the use of models 1 and 2 (Table 2).

Bakirci (2009), using a series of radiometric data for 18 sites of Turkey, calculated different estimation errors from a comparative study between measured and estimated global solar irradiance to determine the best Q_g estimation model. The same author verified that even with models showing the highest coefficients of the Pearson correlation obtained by means of a regression analysis between Q_g measured and estimated values, the statistical parameters that reveal the estimation errors were high, leading to the proposition of adjustment factors to be incorporated into the models for the studied sites.

Determining which model turns out to be the best to calculate Q_g as a function of the estimation errors scuppers the utilization of estimation equations indiscriminately and bereft of scientific criteria of selection at a given site. In a study carried out in Tibet, China, Li et al. (2011) confirmed the utilization feasibility of different models designed to estimate global solar irradiance as a function of the calculation of dispersion measures that express the estimation errors and obtained good approximations of Q_g , with errors below 10% under the local climatic conditions.

The best performance revealed in the current study, either for the first or second models, is intimately

related to the direct interference of atmospheric cloudiness conditions, expressed by global solar transmittance determined locally under extreme cloud cover situations from the monitoring of radiometric data collected at weather stations.

Fittings in the Angström-Prescott classical model to estimate Q_g were proposed by Toğrul (2009) by means of the addition of geographical and meteorological data collected at the region of Bishkek, Kyrgyzstan, being able to notice that such a model showed good estimation results of global solar irradiance.

A similar study was developed by Chen and Li (2012) in the northeast of China, by analyzing radiometric data collected from 13 weather stations. The fitting of the Angström-Prescott classical model was obtained from the calibration of the a and b coefficients as a function of variations of the global transmittance at the studied site. Even under the influence of non significant differences among the installation sites of weather stations and estimation methods employed, the aforementioned authors observed that alterations in the empirical coefficients of the regression equation increased accuracy of the Q_g estimation model.

Despite the third Q_g estimation model has demonstrated a performance index lesser than the other models, such a model was to be quick and practical for evaluation of Q_g as a function of only one radiation maximum flux density measured at solar noon, which is irrespective of daily integrations and does not require a large number of radiometric measurements in projects of solar engineering.

IV. CONCLUSIONS

Daily global transmittance was conditioned to atmospheric cloudiness, being amenable to estimate global solar irradiance for sunny days.

The Angstrom-Prescott classical approach might be used to calculate daily global irradiance with accuracy and exactness in the municipality of Ponta Grossa, PR, Brazil.

Models for which the a and b coefficients were locally obtained as a function of daily mean global transmittance showed estimates more close to radiometric data measured by pyranometers, being such models therefore more reliable for agrometeorological purposes.

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